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A life cycle scenario analysis of different pavement technologies for urban roads

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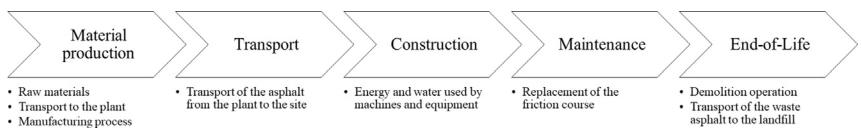
HIGHLIGHTS

- A "from cradle to grave" LCA of a typical Italian urban road is carried out.
- Different scenarios of bituminous mixtures are analyzed.
- RAP mixtures are considered in the bituminous layer.
- WMA technology, combined with RAP, improves the pavement energy and environmental performance.

GRAPHICAL ABSTRACT



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ABSTRACT

In the past, lowest price was the award criterion, given that structural capacity and safety were assured.
In the last years, environmental, energy, and long-term impacts have been introduced (climate change, resource depletion, energy consumption, generated solid waste, discharged water, and emissions).
Unfortunately, the introduction of new pavement technologies and materials (i.e., waste plastics) affects maintenance and rehabilitation processes and call for accurate and timeliness studies and criteria.
Consequently, this paper presents an energy and environmental assessment of an Italian urban road and considers different material-related scenarios that fully comply with emerging technologies.
A life-cycle approach is applied to assess energy and environmental impacts of a typical Italian urban road, according to the ISO 14040 series. In more detail, the authors assess the energy and environmental profile of different scenarios of bituminous mixtures. The aim of scenario analysis is to identify the less impacting scenario from an energy and environmental point of view. For each analyzed scenario, the contribution of each life-cycle step to the total impacts and the energy and environmental hotspots are identified in order to define suitable options for improvement.
The results of the analysis show that step of material production, including raw material extraction and resource supply, is relevant to almost all the assessed impact categories (average contribution higher than 50%). This is mainly due to the production of bitumen, which is a petroleum-based product. Moreover, the scenario analysis highlights that the pavement scenarios that are characterized by the use of recycled materials involve lower energy and environmental impacts, due to the saving of virgin raw materials and avoided impacts for disposal.

1. Introduction

The rapid increase in energy demand and environmental impacts over the past few years requires the development of low-carbon and low-energy consumption at a global level. The reduction of energy requirement and the mitigation of environmental impacts have become key targets of EU policies for climate and energy, to be matched by means of strategies aimed at tackling climate change (European Commission, 2018, 2011; European Council, 2014). In this context, after electricity and heat generation sector, which accounts for 42%, transport accounts for about 23% of global Greenhouse Gas (GHG) emissions in 2013 and for 30% of the total energy consumption (IEA, 2015). Road construction GHG emissions represent 5–10% of total GHG emissions

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in the transport sector, but they are growing rapidly, especially in developing countries due to major ongoing road programs to support economic development (The World Bank, 2011).[1] One of the major challenges of pavement engineering is to meet the ever-increasing demand of economic and natural resources related to construction and maintenance by means of environmentally sustainable technologies (Santero et al., 2011a). Considering that the amount of paved roads tends to grow over the years, special attention has to be given to decrease energy consumption and GHG emissions in sight of environmental sustainability (Araújo et al., 2014; Birgisdóttir et al., 2006).

Several paving technologies have been developed to reduce and mitigate the environmental impacts associated with the use of traditional Hot Mix Asphalt (HMA), such as Warm Mix Asphalt (WMA) (Mohammad et al., 2015), and HMA or WMA containing recycled materials. Among the most popular recycled materials are crumb rubber from end-of-life tires, reclaimed asphalt pavement (RAP) (Aurangzeb et al., 2014; Lee et al., 2010), and industrial wastes and by products (Carpenter and Gardner, 2009), (Mladenovič et al., 2015).

In such a context, to adopt the life-cycle perspective to assess the energy and environmental impacts is becoming ever more important for new technologies on pavement construction.

The scientific literature in the field of road pavement LCA is growing and even more studies show that Life Cycle Assessment represents a useful methodology to support the selection of the preferred paving techniques, including all the phases in which structures and facilities are built, operation, maintenance, renovation, the disassembly, and the waste management (Gulotta et al., 2018; Mistretta et al., 2013).

Santero et al. (2011a, 2011b) provided a summary of the application of LCA to pavements. This reflects the increased attention to the use of the life-cycle approach in assessing the environmental burdens of pavements. They presented recommendations and necessary actions to fill the identified research gaps with respect to construction, use, and end-of-life phases of pavement's life cycle.

Park et al. (2003) reported that the most energy-intensive step in a road life-cycle is the production of construction materials, and stated that the construction and demolition steps account for higher energy consumption than maintenance.

Some studies focused only on the energy consumption and greenhouse gas emissions, not assessing other impact categories. Among these, Thenoux et al. (2007) reported that recycling with foamed bitumen involves a reduction of energy consumption up to 40%. Wang et al. (2018) focused on the energy and GHG emission assessment associated with material production, construction, and pavement use. They included the effects of pavement rolling resistance on vehicle operation, highlighting that: i) for high traffic volumes rolling resistance is more important than construction; ii) for low traffic volume highways, construction quality and material selection play a particularly important role.

Blankendaal et al. (2014) focused on the carbon footprint of roads, and found that material production accounts for 52.3% of the total carbon footprint in newly constructed roads, followed by the maintenance stage (24.3%), with a carbon footprint contribution of 1000–2500 kg CO_{2eq} per km of road. They also discussed how renovation, maintenance, construction, and materials affect the overall carbon footprint for cement concrete and asphalt concrete pavements.

Most of LCA studies show that the use step involves the highest contribution to the life-cycle environmental impacts (Vidal et al., 2013; Yu and Lu, 2012). Moreover, such studies show that, including the use step in a LCA study, the relative shares of road material production, construction, maintenance and end-of-life to the life-cycle energy and environmental impacts are not significant, if compared to the contribution from the use step.

[1] Greenhouse Gas Emissions Mitigation in Road Construction and Rehabilitation. A Toolkit for Developing Countries. The World Bank, 2011. http://documents.worldbank.org/curated/en/660861468234281955/Transport-Greenhouse-gas-emissions-mitigation-in-road-construction-and-rehabilitation-A-toolkit-for-developing-countries.

It can be highlighted that it is difficult to compare different literature studies carried out on LCA of road pavements, since these take into account different methodological assumptions, and different system boundaries and functional units. Moreover, the environmental performance of asphalt pavements is very sensitive to transportation distances, hence the comparisons that can be done are very site-specific (Cross et al., 2011). Further, different electricity mixes, production practices, employed materials, local maintenance practices, and other region-specific elements involve different outcomes which are affected by the location under study.

Such inconsistencies make pavement LCA results difficult to compare and limit their usefulness in a decision-making process.

In order to comprehensively quantify environmental impacts and to guide towards sustainability goals, functional units should be standardized, and data quality and reliability should be improved. This could allow future LCA studies to carry out comparable assessments, in order to create synergies among literature assessments and outcomes.

The existing literature establishes a framework useful to estimate environmental impacts, but fails to deliver global conclusions regarding material choices, maintenance strategies, and other best-practice policies for achieving sustainability goals (Beccali et al., 2007).

In the attempt to overcome the limitations above, this paper presents a LCA study to assess the energy and environmental performances of a typical Italian urban road, according to the international standards of series ISO 14040–14044 (International Organization for Standardization, 2006a, 2006b). The life-cycle energy and the environmental impacts, arisen from the production, transportation, laying operations, maintenance and end of life of road pavement, are assessed in order to identify the main hotspots along the whole life-cycle. This paper takes into account primary energy, measured at the natural resource level, including losses from the processes of extraction of the resources, their transformation and distribution, thereby expressing the environmental load induced by a road pavement in its life-cycle.

Moreover, different road paving technologies are considered and compared in order to identify potential environmental improvements to the examined system from a life cycle perspective.

Based on the above goals, this study intends to provide the following opportunities and insights: 1) need for primary energy savings and environmental impact minimization in the road pavement life-cycle; 2) need for reducing landfills, increasing the reuse of RAP; 3) opportunity of recycling plastics, substituting the corresponding quantities of bitumen modifiers.

The contributions of the paper to the previously described state-of-the-art are: 1) to increase the limited number of road pavement LCA studies, most of which take into account only the energy demand and greenhouse gas emissions, not assessing other impact categories; 2) to support research to improve environmental performance and help all the involved stakeholders towards sustainable solutions (e.g., recycled materials and emerging technologies); 3) to enable policy makers to compare different scenarios at the design stage and/or introduce remediation actions that could suitably modify the overall environmental performances of road infrastructures; 4) to improve LCA research in order to lead industry and government agencies to successful paths towards sustainability goals.

2. Methods: life cycle assessment

2.1. Goal and scope definition

LCA is a useful tool for assessing primary energy demand and environmental burdens related to the full life-cycle of products (Cellura et al., 2017; Mistretta et al., 2019). In this paper, the authors apply an attributional LCA approach, according to the international standards of series ISO 14040 (International Organization for Standardization, 2006a, 2006b). The goals of the study are:

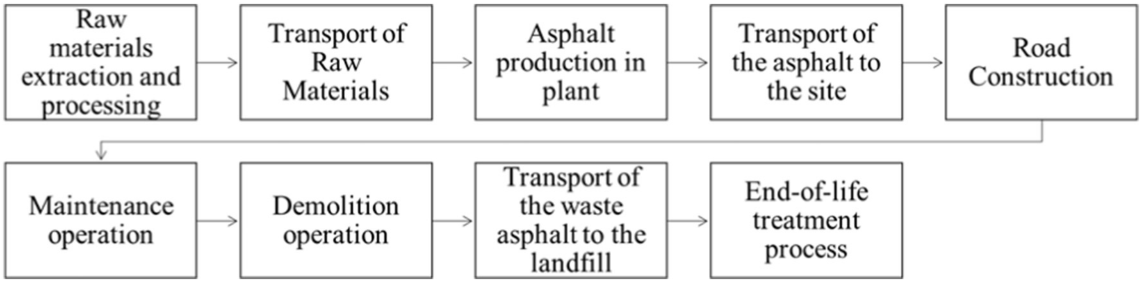


Fig. 1. System boundaries of the assessed system.

- to assess the energy and environmental impacts (eco-profile) of the asphalt pavement of a typical South Italy urban road, following a life cycle approach;
- to identify the hotspots of impacts along the supply chain;
- to identify potential environmental improvement by analysing different types of bituminous mixtures from a life cycle perspective. In detail, different scenarios, based on different construction techniques of road pavement, are defined, and a scenario analysis is carried out in order to identify the less impacting one from the energy and environmental point of view. The contribution of each life-cycle step to the global energy demand and to environmental impacts is assessed. Further the energy and environmental hotspots are identified in order to define suitable options of improvement.

Selection of the type of road to be studied is carried out considering that in Italy there are 172,356 km of sub-urban roads, while 6668 km of motorway (Celauro et al., 2015).

2.1.1. Functional unit and system boundaries

The selected functional unit (FU), which represents the reference unit through which a system performance is quantified in a LCA study, is 1 m^2 of road, as prescribed by the Environmental Product Declaration (EPD) Product Category Rules (The International EPD® System, 2013).

The study includes all the processes and activities that encompass material production, laying operations, maintenance works during pavement lifetime, and end of life, according to a cradle to grave approach.

In detail, the system boundaries include the following steps (Fig. 1):

- Material production, which includes raw material and energy supply (extraction of raw material for all main parts and components and impacts due to the production of electricity and fuels to use in the subsequent steps), and manufacturing stage, which involves handling and processing operations occurring in asphalt plants (which depend on the assumed scenario).
- Laying operations, which include all the processes for the construction of the road.
- Maintenance, which consists of milling and reconstruction of the upper layer of the pavement, in order to ensure functionality, in terms of bearing capacity, surface regularity and friction over the lifespan of the road infrastructure. They include the demolition and discard of damaged material, the production of new material, transport to the site, laying processes, always considering the appropriate equipment and related emission/fuel consumption.
- Transport, including the transport of raw materials from the extraction to the asphalt plant, as well as the transport of the produced materials to the construction site.
- End of life, which includes the definition of the final destination of the materials, in terms of re-allocation as recycling material or disposal as waste.

The manufacturing of production equipment, buildings and other capital goods were not taken into account, because they are not included in the technical system (The International EPD® System, 2013).

With regard to the use phase, the relevance of which is well known in road LCAs, as clearly highlighted in the sector literature, in this study it is omitted, due to the lack of reliable and consistent data for the innovative materials considered in the investigation.

The average lifetime of road pavements, which includes all processes showed before, is difficult to determine and road infrastructure is maintained frequently to ensure an adequate level of service. In this study, lifetime is assumed to be 20 years. For the sake of simplicity, with regard to the maintenance step, milling and reconstruction of the top layer of the pavement (friction course) is assumed as half of the lifespan (10 years), as required by PCR (The International EPD® System, 2013).

With regard to the end-of-life, the main activities related to this phase are demolition (milling) and transportation of materials, to be considered in terms of emissions and fuel use. Leaching should be accounted for, during this phase, depending on the use of the material after demolition.

2.1.2. Models: impact assessment methods and indicators

The life cycle impacts are calculated using SimaPro software.[2] The characterisation models used are the Cumulative Energy Demand method for the Global Energy Requirement estimation (Wernet et al., 2016), and the Environmental Product Declaration (EPD) characterisation factors for the environmental impacts assessment (EPD, 2016).

In detail, the assessed energy and environmental categories are:

- Global Energy Requirement ($MJ_{primary}$);
- Global Warming Potential (GWP, kg CO_{2eq});
- Acidification Potential (AP, kg SO_{2eq});
- Eutrophication Potential (NP, kg PO_{4eq}^{3-})
- Photochemical Oxidation Potential (POCP, kg C_2H_{4eq}).

No allocation procedures are performed. All the energy and environmental loads are attributed to the FU (Ardente and Cellura, 2012).

2.1.3. Definition of case study and of scenarios

The case study under analysis refers to a two-lane, single carriageway road (length 1 km and width 9.5 m), with a pavement thickness of 320 mm. The pavement structure, which lays on the subgrade, is composed of:

- Friction course (mix asphalt, 50 mm).
- Binder course (mix asphalt, 70 mm).
- Unbound base course (granular layer, 200 mm).

Subgrades, embankments, drainages and road marking are not included in the analysis: these aspects are also excluded in previous pavement LCA studies reported in literature (Santero et al., 2011a).

In detail, five different optimized scenarios of bituminous mixtures are defined and compared to a baseline case, named as Reference Scenario, involving the use of standard paving materials. Thus, a scenario analysis, integrated with the LCA methodology is carried out, to assess

[2] https://simapro.com/.

the variations induced in the energy and environmental impacts by the use of recycled materials (Reclaimed Asphalt Pavement, waste plastics, and crumb rubber), and by the asphalt plant characteristics and technology (Hot Mix Asphalt and Warm Mix Asphalt), in order to identify the best alternative in terms of energy and environmental performance.

Hot Mix Asphalts (HMA) are composed of aggregates and asphalt binder and are produced at about 170 °C. Warm Mix Asphalts (WMA) include also additives that allow using temperatures 30–50° lower than traditional HMA. The low production temperatures of WMA build on the reduction in binder viscosity. WMA technologies exhibit environmental benefits related with the reduction of the energy consumption, while technical benefits include better compaction, and the ability to haul paving mix for longer distances (extending the paving season), with the expectation that the mixes have strength, durability, and performance characteristics better than HMAs.

In the Reference Scenario, the friction course is a traditional porous asphalt concrete, which includes HMA, composed of modified bitumen (5% by mix weight) with Styrene-Butadiene-Styrene (SBS) Polymer (SBS), quicklime (QL), cellulose fibres (FB), mineral filler (FIL), and mineral aggregates, with in-place residual air voids of 18%.

The binder course is a dense-graded asphalt concrete (still a type of HMA) that includes neat bitumen (5% by mix weight), mineral filler, and mineral aggregates with in-place residual air voids of 6%.

The unbound base course includes a given gradation of mineral aggregates, compacted at a given moisture content.

Starting from the Reference Scenario, the authors define five supplementary scenarios of paving technologies, as described in the following paragraphs.

Scenario 1 includes no modified bitumen, while waste plastics (WP), and crumb rubber (CR) from end-of-life tires are used. It is assumed that the selected WP derive from municipal solid wastes, as well as CR from waste tyres are used into the friction course, thus addressing at the same time issues that concern land use reduction for disposal, non-renewable resource saving, and climate change mitigation.

Scenario 2 is devoted to the addition of reclaimed asphalt pavement (RAP) in the bituminous mixtures of friction and binder courses. Reclaimed Asphalt Pavement (RAP) is the term given to removed or reprocessed pavement for maintenance or rehabilitation. It contains asphalt and aggregates and can be recycled in the production of the bituminous mixtures. The addition of RAP is addressed to save virgin materials and to avoid undesired impacts to landfills. The main phases involved for RAP-added mixtures are the following (Bonicelli et al., 2017; Praticò et al., 2013):

- RAP in-place milling and transport to the crushing plant (or directly to the asphalt plant);
- RAP pre-processing or pre-treatment (crushing plant, sieving, transport, stockpiling);
- RAP processing at the asphalt plant (heating in the drum; mixing in the mixer).

The remaining processes of RAP-based mixtures are the same as *per* common mixtures (see Reference Scenario). The higher the RAP percentage, the lower the virgin aggregates and the virgin bitumen percentages are.

In Scenario 2, 30% of RAP used in the friction and binder layers of the Reference Scenario. Further a rejuvenating agent is added in order to fulfil bituminous viscosity requirements and increase mix expected life (Praticò et al., 2011).

In Scenario 3 the bituminous layers are supposed the same of the previous scenario, but, in this case, even the unbound base is mixed with RAP (30%). This has positive consequences in terms of landfill volumes and virgin material consumption.

In Scenario 4, a porous and warm mix asphalt (PAWMA) is considered as friction course. It includes mineral aggregates, filler, and modified bitumen, as for Reference Scenario. Organic additive in a standard dosage (0.5% based on bitumen weight) is added in the pursuit of reducing the viscosity of the asphalt binder at a given temperature. Also the binder course is manufactured using the WMA technology. It includes the same components reported above for the PAWMA, where the gradation of mineral filler and aggregates is different and a different asphalt binder percentage is given.

In Scenario 5, the friction course is a PAWMA as for Scenario 4, but in this case it contains 30% of RAP (Praticò, 2004). Similarly, the binder course is composed of WMA with 30% of RAP.

Furthermore, the unbound base layer is mixed with 30% of RAP.

Table 1 shows the main characteristics of the proposed scenarios, while in Table 2 materials used in the road pavement are presented for each of the above defined scenarios.

2.2. Data quality and life cycle inventory

Life Cycle Inventory (LCI) is performed to quantify the energy and environmental significant inputs and outputs of the examined system, by means of mass and energy balances of the selected FU for each scenario. In this section, the authors describe the data collection and the assumption made to model the life cycle phases within the selected system boundaries and to perform the scenario analysis.

Data for LCI, related to material production and construction processes in the road pavement field, are sometimes incomplete, thus LCA experts have to refer to estimate methods (Farina et al., 2017; Santagata and Zanetti, 2012). In the presented case study, LCI data used to model the foreground system (European Commission — Joint Research Centre — Institute for Environment and Sustainability, 2010) are arisen from literature, and/or collected through interviews with local contractors and experts involved in road works.

With regard to material production, primary data are collected through interviews with experts involved in road works. Virgin aggregates are mainly sand and gravel and are assumed to be selected from crushed and sieved fractions from quarries. The related transport distances are calculated assuming that they are extracted from Calabrian and Sicilian quarries.

Secondary data are taken from (Wernet et al., 2016) and from (Blomberg et al., 2011), which provide from-cradle-to-gate LCIs of bituminous materials, representative of the European scenario.

Primary data on the eco-profile of crumb rubber (Scenario 1) are not available, thus information are derived from the literature (Farina et al., 2017). Fuel consumption due to transport of end-of-life tires is calculated assuming the following distances:

- 75 km from the collection point of the end-of-life tires to the processing plant to produce CR.
- 100 km from the CR processing plant to the HMA plant. Further, the benefits derived from the avoided disposal of end-of-life tires are taken into account.

Table 1
Main characteristic of the examined scenarios.

Scenario	Friction course		Binder course		Unbound base course	
	0.05 × 9.5 × 1000		0.07 × 9.5 × 1000		0.20 × 9.5 × 1000	
	Density (kg/m^3)	Weight (ton)	Density (kg/m^3)	Weight (ton)	Density (kg/m^3)	Weight (ton)
Reference	1963.00	932.43	2336.00	1553.44	2000.00	3800.00
Scenario 1	1794.00	852.15	2001.00	1330.67	2000.00	3800.00
Scenario 2	1374.34	652.81	1628.73	1083.10	2000.00	3800.00
Scenario 3	1374.34	652.81	1628.73	1083.10	2284.24	4340.05
Scenario 4	1961.20	931.57	2329.00	1548.79	2000.00	3800.00
Scenario 5	1963.00	932.43	2332.00	1550.78	2000.00	3800.00

Table 2
Materials in the layers for each defined scenario.

Layer	Materials	Reference Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Friction course	AG	X	X	X	X	X	X
	BIT	X	X	X	X	X	X
	CR	–	X	–	–	–	–
	FIB	X	X	X	X	X	X
	FIL	X	X	X	X	X	X
	QL	X	X	X	X	X	X
	RAP	–	–	X	X	–	X
	REJ	–	–	X	X	–	X
	SBS	X	–	X	X	X	X
	WP	–	X	–	–	–	–
	WAT	–	–	–	–	–	–
	Z	–	–	–	–	X	X
Binder course	AG	X	X	X	X	X	X
	BIT	X	X	X	X	X	X
	CR	–	X	–	–	–	–
	FIB	–	–	–	–	–	–
	FIL	X	X	X	X	X	X
	QL	X	X	X	X	X	X
	RAP	–	–	X	X	–	X
	REJ	–	–	X	X	–	X
	SBS	–	–	X	X	–	–
	WP	–	X	–	–	–	–
	WAT	–	–	–	–	–	–
	Z	–	–	–	–	X	X
Unbound base course	AG	X	X	X	X	X	X
	BIT	–	–	–	–	–	–
	CR	–	–	–	–	–	–
	FIB	–	–	–	–	–	–
	FIL	X	X	X	X	X	X
	QL	–	–	–	–	–	–
	RAP	–	–	–	X	–	–
	REJ	–	–	–	–	–	–
	SBS	–	–	–	–	–	–
	WP	–	–	–	–	–	–
	WAT	X	X	X	X	X	X
	Z	–	–	–	–	–	–

AG = mineral aggregates; BIT = bitumen; CR = crumb rubber; FIB = cellulose fibres; FIL = mineral filler; QL = quick lime; RAP = reclaimed asphalt pavement; REJ = rejuvenating agent; SBS = styrene-butadiene-styrene polymer; WP = waste plastic; WAT = water; Z = synthetic zeolites.

No assessment of CR co-products recycling (steel and textile) has been performed. Data on RAP are extracted from an available study on its use in road pavements (Giani et al., 2015).

Primary data concerning electricity consumption of equipment used in quarries and asphalt plants are collected from contractors in Calabria Region, which provided figures based on yearly averages. In the case of vehicles and machineries involved in construction and maintenance operations, calculations are based on average hourly fuel consumption data and on reference values of productivity and working hours, available in the literature (Huang et al., 2009). Data on machinery performance, diesel consumption, natural gas consumption, and electricity consumption are obtained from the literature (Zapata and Gambatese, 2005).

The eco-profiles of energy sources, raw materials, transports, and waste treatments are included in the analysis based on international environmental databases (Wernet et al., 2016). In particular, the eco-profile of electricity is referred to the Italian electricity mix. The eco-profiles of input materials are mainly referred to the European context.

For each defined scenario, LCI is performed on the basis of the data listed in Table 3, which shows the amounts per FU of the different materials used in pavement layers, and of the average haul distances from production/supply sites to the road construction site.

Laying operations are accomplished using different types of equipment. In this phase, the environmental burdens are due to the combustion-related emissions from equipment.

The primary energy demand during the layer construction is calculated considering data shown in Table 4. Diesel consumption of machinery used in place to compact layers are calculated, taking into account hourly fuel consumption of construction equipment.

With regard to the maintenance step, one replacement of the friction course after ten years from the construction is assumed. Fuel and water consumptions, due to the reconstruction of the friction course are added to those deriving from the milling of the old damaged surface layer and from the transportation of the removed material to a landfill located at 100 km.

2.3. Life cycle impact assessment (LCIA)

LCIA results are shown in the following section, which highlights different aspects of the energy and environmental performance associated to the six assessed scenarios of road pavements.

Section 2.3.1 provides a description of the life-cycle energy demand in terms of GER, and Section 2.3.2 describes the environmental impacts.

2.3.1. Life-cycle energy demand: GER

GER is calculated as the total primary energy demand of the whole life cycle of the road pavement.

Table 5 shows the results of GER for each investigated scenario. Outcomes show that, while the Reference Scenario presents the highest value of GER (2024.62 $MJ_{primary}/m^2$), Scenario 5 (PAWMA with 30% of RAP) involves the lowest GER (1815.28 $MJ_{primary}/m^2$), with a reduction of 10% in comparison with Reference Scenario. This result is essentially due to the lower consumption of energy in WMA production and to the use of RAP in the pavement layers, which implies a reduction of virgin raw materials requirement. A similar reduction occurs in Scenario 1, due to the use of materials containing CR and WP.

Material production step involves the most significant contribution, and accounts for about 70% of GER in each scenario.

Table 3
Quantities per FU and transport distances of employed component materials in pavement for each scenario[a].

Materials	Reference		Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
	kg/FU	km	kg/FU	km	kg/FU	km	kg/FU	km	kg/FU	km	kg/FU	km
AG	557.90	196.00	504.30	196.00	491.44	196.00	414.14	196.00	557.14	196.00	482.04	196.00
BIT	12.43	348.00	10.01	348.00	10.04	348.00	10.04	348.00	12.63	348.00	9.61	348.00
CR	–	–	13.12	100.00	–	–	–	–	–	–	–	–
FIB	0.29	205.00	0.27	205.00	0.32	205.00	0.32	205.00	0.29	205.00	0.29	205.00
FIL	43.42	196.00	42.52	196.00	44.04	196.00	35.46	196.00	43.41	196.00	43.42	196.00
QL	7.33	460.00	6.43	460.00	7.78	460.00	7.78	460.00	7.31	460.00	7.32	460.00
RAP	–	–	–	–	83.22	100.00	220.28	100.00	–	100.00	78.42	100.00
REJ	–	–	–	–	0.25	348.00	0.25	348.00	0.06	348.00	0.24	348.00
SBS	0.29	348.00	–	–	0.30	348.00	0.30	348.00	0.25	348.00	0.20	348.00
WP	–	–	13.12	100.00	–	–	–	–	–	–	–	–
WAT	40.00		40.00		40.00		45.68		40.00	–	40.00	–
Z	–		–		–		–		0.07	348.00	0.10	348.00

AG = mineral aggregates; BIT = bitumen; CR = crumb rubber; FIB = cellulose fibres; FIL = mineral filler; QL = quick lime; RAP = reclaimed asphalt pavement; REJ = rejuvenating agent; SBS = styrene-butadiene-styrene polymer; WP = waste plastic; WAT = water; Z = synthetic zeolites.
[a] The quantities of materials have been assumed by the Authors, depending on the pavement construction techniques, the composition of the layers, and the different scenarios under study.

With regard to construction step, the scenarios with RAP involve a slight increase (13%) respect to the Scenarios without RAP, due to higher energy required for the milling process.

About the maintenance step, it is foreseen one replacement of the friction course layer during the pavement lifespan in all the scenarios. It accounts for 18–19% of the total GER, and includes the contribution of the transport from the paving site to landfill and the waste asphalt management. With regard to transport and end-of-life, GER is around 5–6% in all scenarios.

Fig. 2 shows the contribution of materials to GER in the production step. The main contribution to GER comes from virgin bitumen production (about 70% in Reference scenario and Scenario 4), while Scenarios with recycled materials show lower shares (nearly 60%), followed by filler production, which provides a contribution varying from 21% (Scenario 3, Reference Scenario) to 27% (Scenarios 2 and 5). Quicklime accounts for 5–6% in the production GER in all the scenarios, while mineral aggregates contribute for about 3%.

2.3.2. Life-cycle environmental impacts

Life-cycle environmental impacts of the road pavement, referred to the FU, are showed in Table 6 for all the assessed scenarios. For each impact category the results show slight differences among the assessed scenarios.

With regard to GWP, Reference Scenario involves the biggest value of GWP (90.6 $kgCO_{2eq}/m^2$), while Scenarios 1, 4, and 5 involve the lowest contribution (about 87 kg CO_{2eq}/m^2).

With regard to AP, NP, and in POCP the scenarios containing RAP (Scenarios 2, 3, and 5) present slight higher shares. Fig. 3 shows a contribution analysis to identify the life-cycle steps, which involve the most significant share to the assessed environmental impact indicators.

The outcomes highlight that material production phase causes the highest share in almost all the assessed impact categories, varying from nearly 60% to 70%. The contribution of production step to NP varies from 3% to 24%.

With regard to transport, it involves the highest contribution to GWP, accounting for nearly 8% in all the scenarios, while its share to AP, NP and POCP is not more than 3%.

Construction step involves a contribution not higher than 1% to each impact category in all the assessed scenarios.

With regard to the maintenance step, referred to the replacement of the friction course after 10 year of lifespan, in all the assessed scenarios it involves a contribution of about 14–15% in GWP, AP, and NP, and a contribution that varies from 22% to 38% in POCP. With regard to the end-of-life, it contributes for about 60–80% to NP.

3. Discussion

In the eco-profiles assessed based on different bituminous mixtures for road pavement, the scenario analysis has been carried out in order to identify the less impacting one from the energy and environmental point of view. The contribution of each life-cycle step of road pavement on the overall impacts has been assessed in order to identify the steps and processes responsible of the highest impacts.

Table 7 shows the percentage variations of the life cycle energy and environmental impacts linked to the scenarios investigated with respect to the Reference Scenario. The analysis shows that all the assessed scenarios show lower GER and GWP, in comparison to the Reference Scenario.

The use of waste plastics and crumb rubber from end-of-life tires in Scenario 1 involves reduction in all the impact categories. In particular, it shows the most significant reduction in POCP (−68%).

Scenarios with RAP (Scenarios 2, 3, and 5) show the increase of AP and NP.

Starting from the above LCA results the following considerations can be traced:

- The picture of the whole life cycle describes different results that do not identify clearly the best scenario among all the six cases for all indicators.

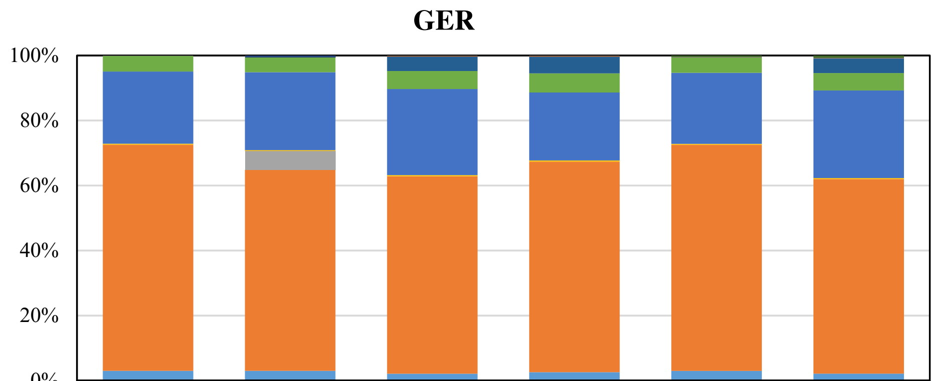
Table 4
Equipment used for the road construction[a].

Equipment	Operating time (h)	Fuel (l/h)	Water (l/h)
Paver	26.60	26.00	40.00
Compactor	3.60	8.00	50.00
Dump truck	1.20	19.00	–
Milling equipment	9.00	100.00	287.00
Grader	0.28	30.00	–

[a] Data derive from interviews with local experts involved in road works, and from standard data input sheets on site machinery used for placement and/or removal operations, which are available in the market and commonly used and available on websites.

Table 5
GER of road pavement per FU: contribution of life-cycle steps for each assessed scenario ($MJ_{primary}/m^2$).

Step	Reference scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Production	1424.41	1275.24	1292.48	1273.68	1387.75	1277.25
Transport	103.75	98.75	106.20	115.13	103.67	103.71
Construction	6.22	6.22	6.52	7.03	6.22	7.03
Maintenance	385.66	345.25	348.85	348.96	374.56	322.76
End-of-life	104.58	99.54	107.05	116.05	104.50	104.50
Total	2024.62	1825.00	1861.10	1860.85	1976.70	1815.28



	Reference	S1	S2	S3	S4	S5
Z	-	-	-	-	4.49	6.41
WP	-	4.01	-	-	-	-
WAT	-	-	-	-	-	-
SBS	1.25	-	1.27	1.27	1.04	0.84
REJ	-	-	1.52	1.52	0.39	0.59
RAP	-	-	38.77	42.03	-	37.86
QL	45.25	39.73	48.04	48.04	45.15	45.20
FIL	208.80	204.46	230.79	170.48	208.72	227.77
FIB	2.73	2.50	3.01	3.01	2.73	2.73
CR	-	49.07	-	-	-	-
BIT C	654.34	526.93	528.46	528.46	664.92	505.72
AG	28.37	25.65	18.48	21.06	28.33	18.00

Fig. 2. GER of materials production in each scenario ($MJ_{primary}/m^2$).

- The life cycle contribution analysis of each investigated scenario highlights that the production phase is the most significant phase, since it involves the highest contribution in all the examined impact categories, with a contribution of 60–70%. The exception is represented by NP in which the most significant share is given by the end-of-life phase in all the assessed scenario.
- The use of WMA in bituminous mixtures, coupled with the use of recycled materials involves lower GER and environmental impacts. In particular, combining WMA with the use of RAP allows reducing the consumption of virgin bitumen and aggregates, thus involving reduction in primary energy consumption and raw materials, and avoiding impacts for disposal.

The results for the material production step show the need to implement measures to reduce energy demand and environmental impacts. Thus, eco-design of production should be investigated more in detail and eco-design solutions should be checked to improve the eco-profile of the road pavement, but not forgetting that a pillar for the sustainability development is the integration between environmental friendly production systems and technological feasibility.

Moreover, the results show that use of recycled and waste materials (RAP, CR, and WP) represents a viable strategy to promote resource and energy efficiency, thus contributing to UN Sustainable Development Goals of Agenda 2030. In such a context, the authors intend to continue the presented research in order to identify strategies of primary energy saving in the material production and transport steps, focusing on the renewable energy source employment.

4. Conclusions

The analysis proposed in this paper marks the concept of providing a systemic approach for life-cycle energy and environmental impact assessment for the sake of all stakeholders, in order to support the development of new models of low-energy consumption and innovative production models in the road field. Benefits can be better policies with clear environmental objectives, more sustainable business strategies, and environmentally friendly product design. Thus, LCA-based metrics can contribute significantly to the Sustainable Development Goals.

In particular, the LCA results obtained in this paper show that recycled materials, coupled with Warm Mix Asphalts can lead to benefits in terms of energy saving and environmental impact minimization. Thus, the use of such materials in road paving technologies can be attractive for policy makers, since it represents an example of resource efficiency and sustainable waste management, limiting land use for landfill and the consumption of natural aggregates.

From a methodological point of view, the literature review showed the difficulty to compare different studies, due to different

Table 6
Life-cycle environmental impacts of the road pavements.

Impact category	Reference scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
GWP (kg CO_{2eq})	9.06E+01	8.70E+01	8.82E+01	8.81E+01	8.65E+01	8.70E+01
AP (kg SO_{2eq})	7.38E−01	7.08E−01	1.02E+00	1.06E+00	6.96E−01	1.00E+00
NP (kg PO_{4eq}^{3-})	7.05E−01	6.30E−01	9.33E−01	9.96E−01	7.00E−01	9.03E−01
POCP (kg C_2H_{4eq})	1.27E−01	4.09E−02	1.33E−01	1.36E−01	1.11E−01	1.26E−01

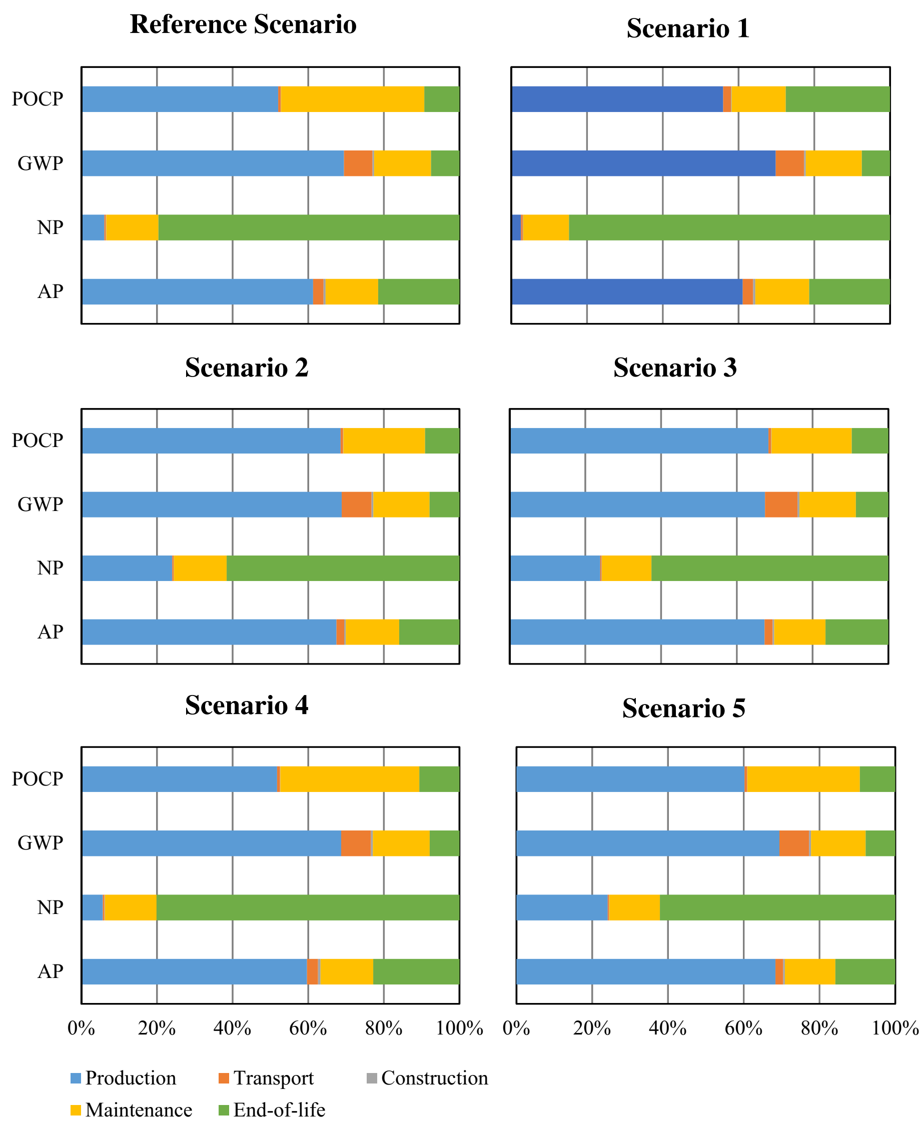


Fig. 3. Contribution analysis of life-cycle environmental impacts.

methodological assumption regarding to functional unit and system boundaries. With regard to functional unit, the authors selected 1 m^2 of road, following the prescription of the Environmental Product Declaration (EPD) Product Category Rules.

One key issue of the analysis is the selection of secondary data for modelling the life-cycle of a number of production materials, due to the limited availability of process-specific data for such materials. This lack of data is mainly linked to the fact that there is a very high number of chemical agents that can be used, and no appropriate measurement of the life-cycle impacts can be possible for all of them. For these products it is necessary to make use of estimates from literature data and this may cause uncertainties in the study.

Table 7
Percentage variations of the life cycle energy and environmental impacts linked to the scenarios investigated with respect to the Reference Scenario referred to FU.

Impact category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
GER ($MJ_{primary}$)	−10	−8	−8	−2	−10
GWP (kg CO_{2eq})	−4	−3	−3	−4	−4
AP (kg SO_{2eq})	−4	28	34	−6	26
NP (kg PO_{4eq}^{3-})	−11	32	41	−1	28
POCP (kg C_2H_{4eq})	−68	5	7	−12	−1

Even though the results obtained are promising, this paper needs to be considered as preliminary, since calculations were based on several hypotheses and estimates. For this reason, the application of a sensitivity analysis on the initial assumptions is quite relevant for the reliability of the results. In this field the authors are still investigating and carrying out a further research activity. In future studies, the authors will try to overcome these limits by monitoring production, construction laying, and use phase, thus leading to a more complete and reliable set of Life Cycle Inventory data.

Despite the limitations above, outcomes show that the LCA methodology can support the development of studies that aim at reducing energy and environmental and can provide a systemic approach for energy and environmental assessment for the sake of all stakeholders, in order to support the development of the eco-design in the road fields, voted to low-carbon and low-energy production models.

The adoption of the LCA approach ensures a systemic accounting of primary energy consumption and other environmental impacts, like GWP, linked to the road pavement, avoiding the shift from one life cycle phase to another. Moreover, it allows identifying the main area of intervention and the most effective strategies.

Public authorities and other stakeholders involved could benefit from basing the management practices and climate strategies upon scientific evidence, e.g. in the context of Green Public Procurement Criteria

for Road Design, Construction and Maintenance, green products, and EU Environmental Product Declarations.

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